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Probe measurements on the P-4 system in single cathode operation.

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Radiation Laboratory

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(Thesis for M. S. degree in physics from the U. S. Naval Postgraduate School)

Duane M. Gall
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PROBE MEASUREMENTS ON THE P-4 SYSTEM IN SINGLE-CATHODE OPERATION

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ABSTRACT

In this report the plasma of the P-4 system in single-cathode operation is examined by probe techniques and compared with data taken previously in two-cathode operation. Although no radical differences were discovered, the data as summarized in Tables 1 and 2 and Figs. 7 through 12 confirms the visual observation that the plasma column is more sharply defined in single-cathode operation.

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INTRODUCTION

In a previous report[1] mention was made of the fact that in the P-4 system two methods of operation were possible: one with the second cathode of the PIG discharge grounded, the other with the second cathode floating, i.e., in effect with only a single cathode. With the condition of the second cathode being grounded a visible haze surrounded the dense portion of the plasma beam. This haze disappeared when the cathode was allowed to float. In the previous report all the probe data presented were taken with the second cathode grounded. Since then, however, additional probe measurements have been made with this cathode floating. It is the purpose here to present this new data and compare it with the previous data.[2]

I. THE P-4 SYSTEM[1]

The P-4 system achieves a highly ionized He plasma by preferentially removing neutral particles from the dense plasma in which they initially predominate. To accomplish this, charged particles are allowed to diffuse along a magnetic field through a region where the neutrals may be pumped away by diffusion pumps or ionized by collisions with electrons. One attempts, in the downstream region to reflect as much of the plasma as possible and eliminate that which is not reflected without causing an excessive rise in neutral particle density. Figure 1 shows schematically the system in its present configuration. It consists of three principal elements: (a) the open-ended discharge region, which is the prime plasma source; (b) the magnetic channel region, where the plasma is guided along magnetic field lines past a series of five pumping stations, each consisting of two 6-in. oil diffusion pumps, in order to remove neutral particles from the incompletely ionized plasma;[3] and (c) the burial chamber for eliminating ions which leak out the downstream end of the system. This burial chamber consists of two magnetic mirrors by which to reflect as much plasma as possible and three 10-in. oil diffusion pumps to remove neutrals formed when electrons and ions which leak past the mirrors recombine at the walls. The opposing magnet is

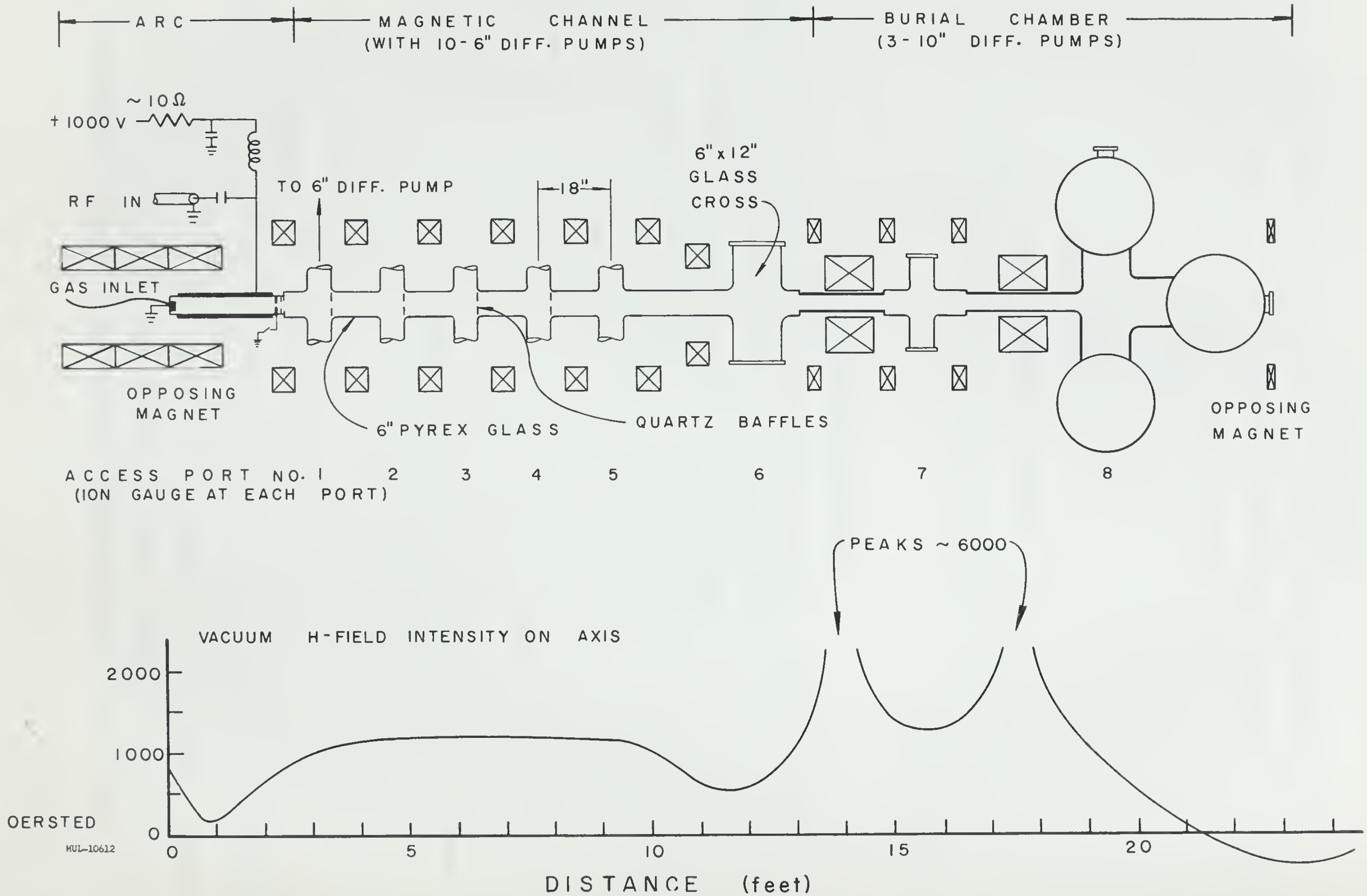

Fig. 1. Schematic drawing of the P-4 system (plan view).

to protect the quartz vacuum window at the end by dispersing stray plasma in the burial chamber.

Some typical features of the plasma are listed below:

Beam Diameter: About 1 in. in the magnetic channel region. This is enclosed by a cooler, less dense shell of about 2 to 3 in. which is determined by the quartz apertures located along the channel.

Ion Temperature: Up to about 8 ev, depending on operating conditions.

Electron Temperature: From 2.5 ev (2.8 cm from beam axis) to 8 ev (0.8 cm from the axis). These are indicated by probe measurements. As yet probes have been used no farther into the beam than a distance of 8 mm from the axis due to melting of the probes. Spectroscopic data indicates electrons of at least 77 ev in the plasma core.

Electron Density: About 2×10^{13} electrons/cm^3 on the axis near the downstream end of the system, by microwave measurements. The probe measurements indicate that this drops to about 5.4×10^{11} electrons/cm^3 at a radius of 2.8 cm.

Percentage Ionization: The ratio of neutral density outside the plasma beam to electron density of the core is about 0.02 in the downstream region, corresponding to about 98% ionization.

Plasma Potential: By probe measurements this is within about 10% of anode potential at the outer boundary and falls about 20 volts as the probe is moved radially inward to the edge of the dense plasma core.

II. GENERAL PROBE THEORY

The theory of cylindrical probes drawing orbital-motion-limited current which was first developed by Langmuir and Mott-Smith[4] did not consider the presence of strong magnetic fields such as is encountered in the P-4 (B ~ 1 kilogauss). Due to the small gyro-radius of the electrons this theory is invalidated as far as electrons in P-4 are concerned. However, this particular objection does not apply to the ions whose gyro-radius is relatively large (~ 1 cm) compared to the probe. Wentzl[5] and also Bohm, Burhop and Massey[6] have applied conventional Langmuir theory to the collection of ions, but in order to do so have used an "effective" ion temperature. Since the conditions when this is valid may not occur in the P-4 system, it was decided to use probes to determine the electron temperature by the retarding field method and to determine only approximate values of plasma density and space potential.

If one considers a cylindrical probe drawing orbital-motion-limited currents, the theory developed by Mott-Smith and Langmuir[7] gives the following relationship for singly charged ions*:

$$J_i^2 = \frac{2\, e^2 k T_i}{\pi^2 m_i} \left[1 + \frac{e(V_s - V)}{k T_i} \right] n_i^2$$

where J_i = ion current density to the probe
V = probe potential
V_s = space (plasma) potential
T_i = ion temperature
m_i = ion mass
n_i = ion density
k = Boltzmann constant
e = electronic charge

Wentzl and also Bohm, Burhop and Massey came to the conclusion that T_i in the above equation is not the true ion temperature, but if the electron temperature is much larger than the ion temperature the electron temperature may be substituted for T_i and correct results will be obtained. In the case of the P-4, two objections to this method come to mind. First, in the P-4 system, the electron temperature is probably not much greater than the ion temperature and second, V_s is a rather poorly defined quantity. However, if one wishes to use probes to determine only n_i, then from the above relationship it can be seen that

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*It is assumed that in the region investigated in P-4 essentially all ions are singly charged.

$$\frac{dJ_i^2}{dV} = - \frac{2e^3}{\pi^2 m_i} n_i^2 \qquad (1)$$

The above equation is independent of T_i. There is some indication from a modified probe theory being developed by L. S. Hall[8] that the above expression should be multiplied by a correction factor of the order of one for the P-4 device. Since this correction factor has not as yet been determined the approximate values of n_i obtained by the original Langmuir and Mott-Smith theory will be used.

In addition to being able to obtain n_i from the slope of a J_i^2 vs V curve, one has the familiar Boltzmann relationship:

$$I_e = I_e^0 \exp\left[- e(V_s - V)/kT_e\right], \quad (V_s - V) > 0$$

where I_e = electron current

T_e = electron temperature

and from this relationship:

$$\frac{d \ln I_e}{dV} = \frac{e}{kT_e} \qquad (2)$$

Thus by the retarding field method one can obtain a plot of ln I vs V, and from its slope get the electron temperature. It is also possible to obtain the value of the space or plasma potential (V_s) from the same plot, provided high enough values of current are reached.

To the extent that these three quantities (T_e, n_i and V_s) are determined it is then possible to infer additional quantities as will be discussed later.

III. PROBE MEASUREMENTS

A. The Probe and Associated Circuitry

The active region of the probes used to take the data for this report was cylindrical tungsten, 1/8 inch long and of 4 or 7 mils diameter. Figure 2 is a sketch of these probes. In operation they are located on a

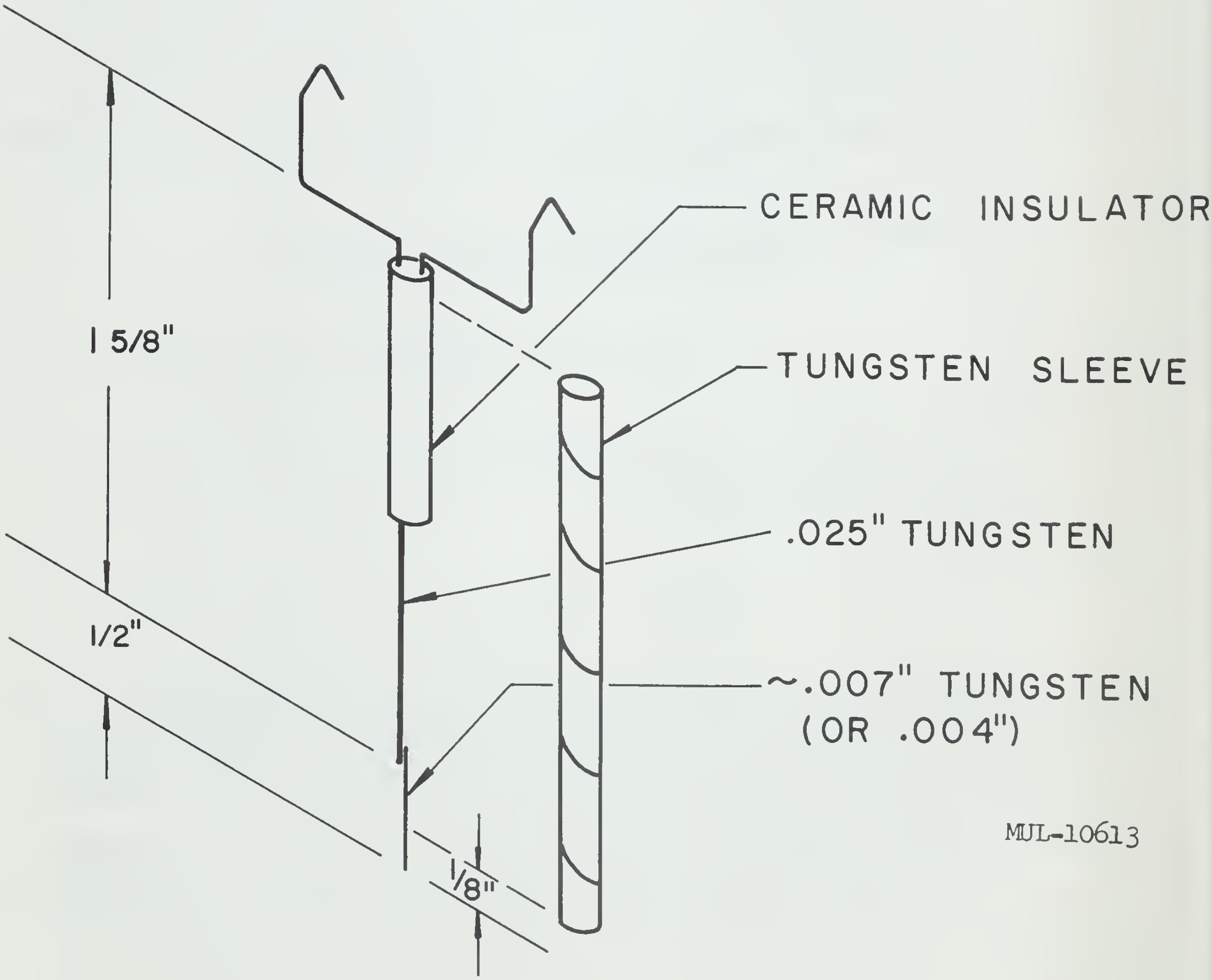

Fig. 2. Langmuir probe used in the measurements.

rack inside the P-4 vacuum system. This allows the experimenter to quickly replace probes should one become damaged. It should be pointed out that for the two probe runs in this report, only one probe was used for each run. Unfortunately, these probes burn up when inserted too far into the beam; consequently at the present time the point of closest approach to the center is about 8 mm. It is expected that at a later date a moving (rotating) probe will allow a complete probe analysis of the beam.

Initially, point-by-point measurements were made of probe current at various voltages. This method was not only slow, but the probes were easily melted as they approached saturation current. In order to avoid burnup from this cause and consequently to be able to operate the probe farther into the beam, the light from the probe was focused on a light-activated relay which opened the circuit when the probe became overheated. In addition, the current-voltage characteristic was visually presented on the face of an oscilloscope and photographed. This allowed one to obtain a complete current-voltage characteristic at a given radius in a very short time with less danger to the probe.

Another advantage of the sweeping technique was to reduce the effect of electron emission, which could be rather large when the probe was sufficiently negative with respect to the plasma potential. When the voltage was swept rapidly enough that the probe could not become too hot the ion current was found to increase uniformly as the probe was made negative with respect to the plasma, showing that electron emission was not important. However, if the voltage was swept too slowly electron emission was indicated by the large increase of current as the probe was made more negative. Figure 3a is an oscilloscope photograph of the probe current-voltage characteristic when the sweep speed was sufficient to avoid appreciable thermionic emission and Fig. 3b is a photograph when the sweep speed was too slow. The effect of the voltage sweep speed on the curves in the region of positive ion collection is apparent.

Figure 4 is a schematic diagram of the probe circuit. The voltage is not only applied to the probe, but serves as the horizontal sweep of the

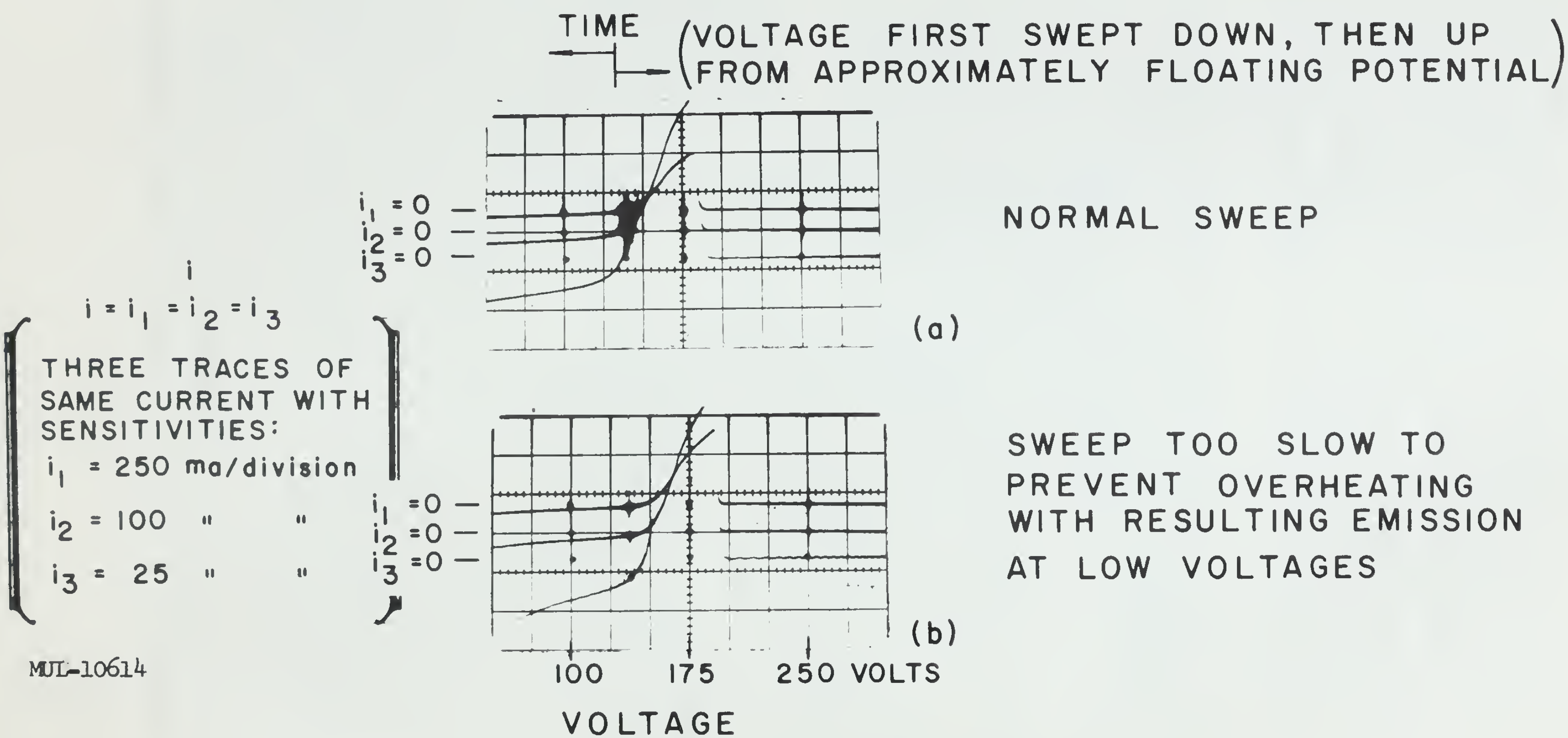

Fig. 3. Probe characteristic curves.

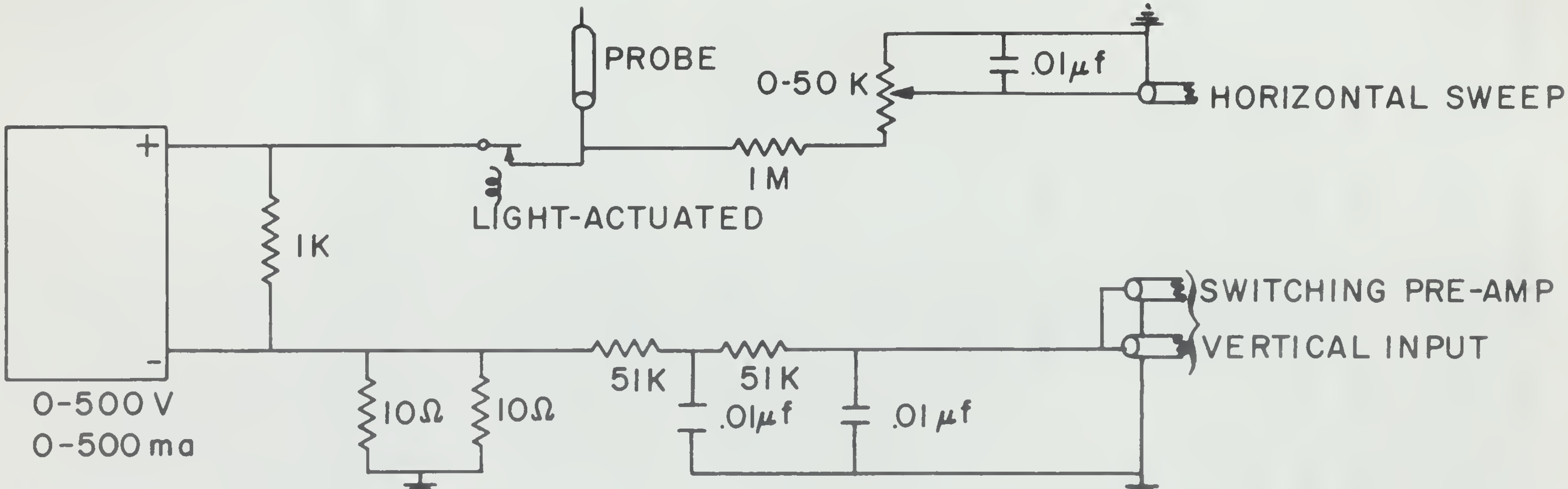

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Fig. 4. Schematic diagram of probe circuit.

oscilloscope after first going through a filter network. The probe current flows through a nominal 5-ohm resistance to develop the vertical voltage input for the oscilloscope. The switching pre-amplifier was used in order to provide two current scales. This was necessitated by the wide range of current collected. A filter network was used on the vertical input to eliminate high frequency noise generated by the plasma. Since the power supply had a very high impedance to reverse current, it was found necessary to parallel the output with a 1000-ohm resistor to prevent the plasma from holding up the voltage across the output terminals of the power supply.

B. Method of Analysis

Once a series of photographs* similar to Fig. 3a were obtained, a comparator was used to measure the resulting deflection due to the probe current at various voltages. If one then plots current squared, I^2, vs voltage as in Fig. 5, and assumes that in the region where probe voltage is very negative with respect to plasma potential no electrons are collected, I_i^2 can be determined as a linear function of V and extrapolated to higher values of voltage. From the slope of these lines one can obtain n_i by Eq. 1.

In addition, when I_i is obtained from the extrapolation of the linear portion of the I^2 vs V plots, it can be subtracted from I (total current) to get the electron current I_e. By plotting log I_e vs V as in Fig. 6 and

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*Representing the current-voltage characteristics of the probe at different radial distances from the beam axis under the same operating conditions.

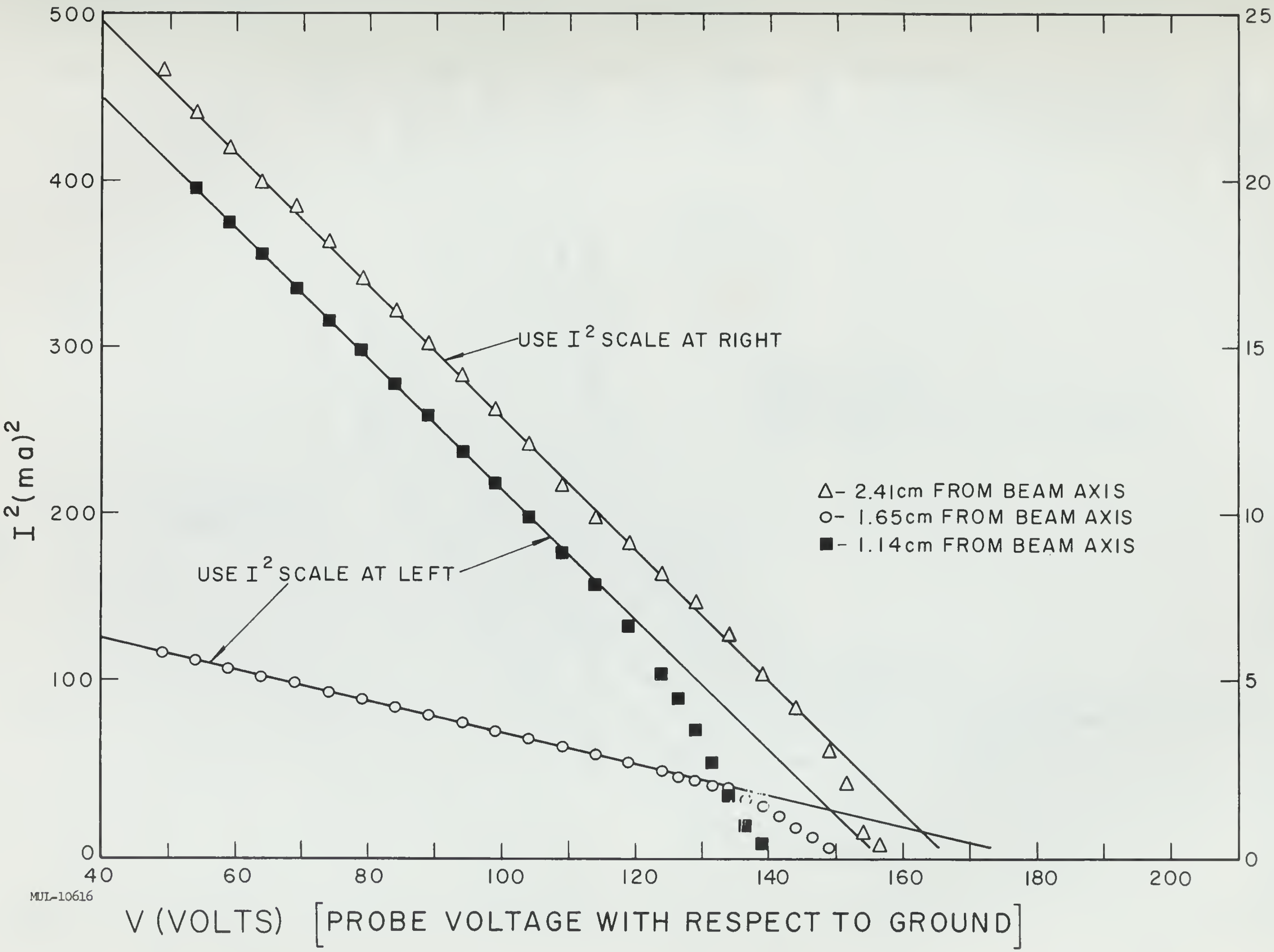

Fig. 5. I^2 vs V, for V less than floating potential.

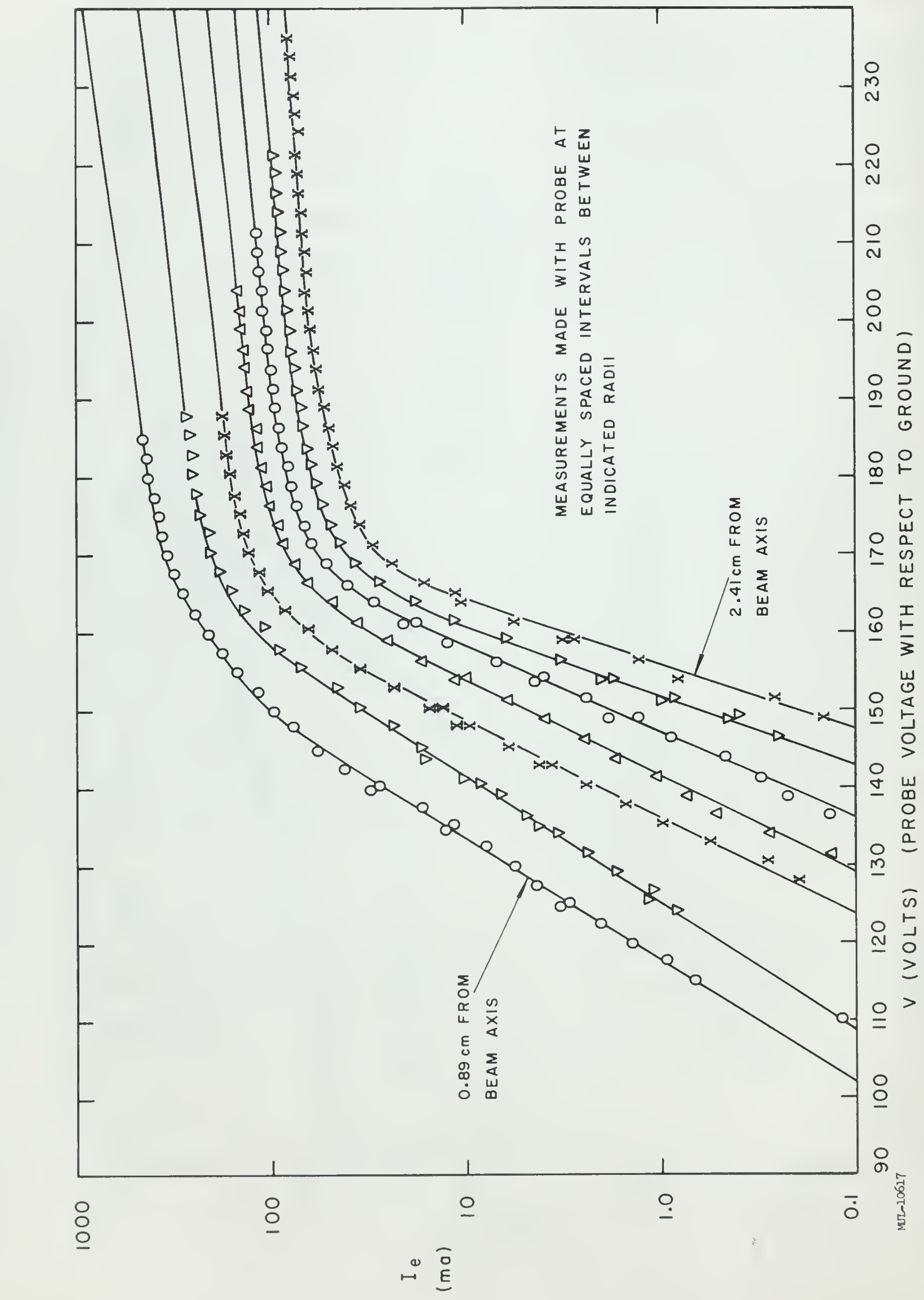

Fig. 6. Log I_e vs V.

using Eq. 2, the electron temperature is obtained.* The fact that a straight-line portion is obtained indicates that there is indeed a Maxwell distribution of electrons.

It is also possible to obtain estimates of space potential from the I_e vs V plots for the purpose of determining radial electric fields in the plasma. At this point the experimenter is faced with several ways of making this estimate: (a) determination of the point where electron current ceases to have an exponential dependence on potential; (b) determination of the shift of the zero potential by matching the "knees" of the curves in Fig. 6; or, (c) determination of the potential (= V_σ) at which two asymptotes of the I_e vs V plot intercept. All of these methods were tried, each yielding essentially the same results. Since method (c) is by far the easiest and most consistent it is this value which is reported herein.

If one recognizes the fact that V_σ is only an estimate of the plasma or space potential (V_s) it becomes appropriate to look for a method of improving this estimate. One such method which comes to mind and was

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*A widely used, and simpler experimental procedure is to linearly extrapolate I_i toward higher potentials and subtract its value from I to get I_e. At first glance this might appear justified because the original I vs V characteristics look reasonably linear in the large negative potential region and the resulting log I_e vs V plots have a linear portion from which T_e can be obtained. However, from the goodness of fit of Fig. 5 and the fact that the log I_e vs V plots are linear from close to space potential down to the smallest meaningful values of electron current, it seems much more appropriate to use the I_i^2 extrapolation. In almost every case the semi-logarithmic plot obtained by using the simpler method shows significant departure from linearity in the region of small I_e. It should be noted that this nonlinearity has sometimes been erroneously interpreted as evidence of two electron distributions with different temperatures.

used in this report is as follows. The floating potential (V_f), which can be measured very accurately, can be expected to differ from the true space potential by a term proportional to the electron temperature. The same is true for V_σ although the factor multiplying T_e should be much smaller. Since both V_σ and V_f may be expected to differ from V_s by a linear term in T_e, then their difference ($V_\sigma - V_f \equiv \Delta V$) must also be linear in T_e. Taking data at various radii it is possible to plot ΔV vs T_e as in Figs. 7a and 7b.* Provided the assumptions that $V_s - V_\sigma = C_1 T_e$ and $V_s - V_f = C_2 T_e$ are correct, in both cases (second cathode grounded or floating) the straight line obtained had a slope:

$$d\Delta V/dT_e = 3.3$$

By the use of this technique the quantity V'_σ, the corrected value of V_σ, is defined as

$$V'_\sigma \equiv V_f + 3.3\ T_e$$

V'_σ has an error characterized by the determinations of V_f, T_e and $1/\sqrt{N-1}$ times the error in the determination of V_σ where N is the total number of such measurements.

C. Results

Tables I and II summarize the data obtained from the probe analysis with the second cathode in the grounded and floating conditions respectively, i.e., double- or single-cathode operation.** Figure 11 is a plot of n_i, the

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*The assumption was made in both cases that at $T_e = 0$, $\Delta V = 0$, i.e., a one-parameter least-squares fit was made.

**It should be noted that the anode voltage in the two cases was not the same. In the past it has been observed that the anode voltage has no significant effect on the plasma density or temperature nor on the shape of the curves of the parameters discussed in this report. It is for this reason that differences in the probe data for the two cases (single- and double-cathode operation) is not attributed to differences in anode voltage.

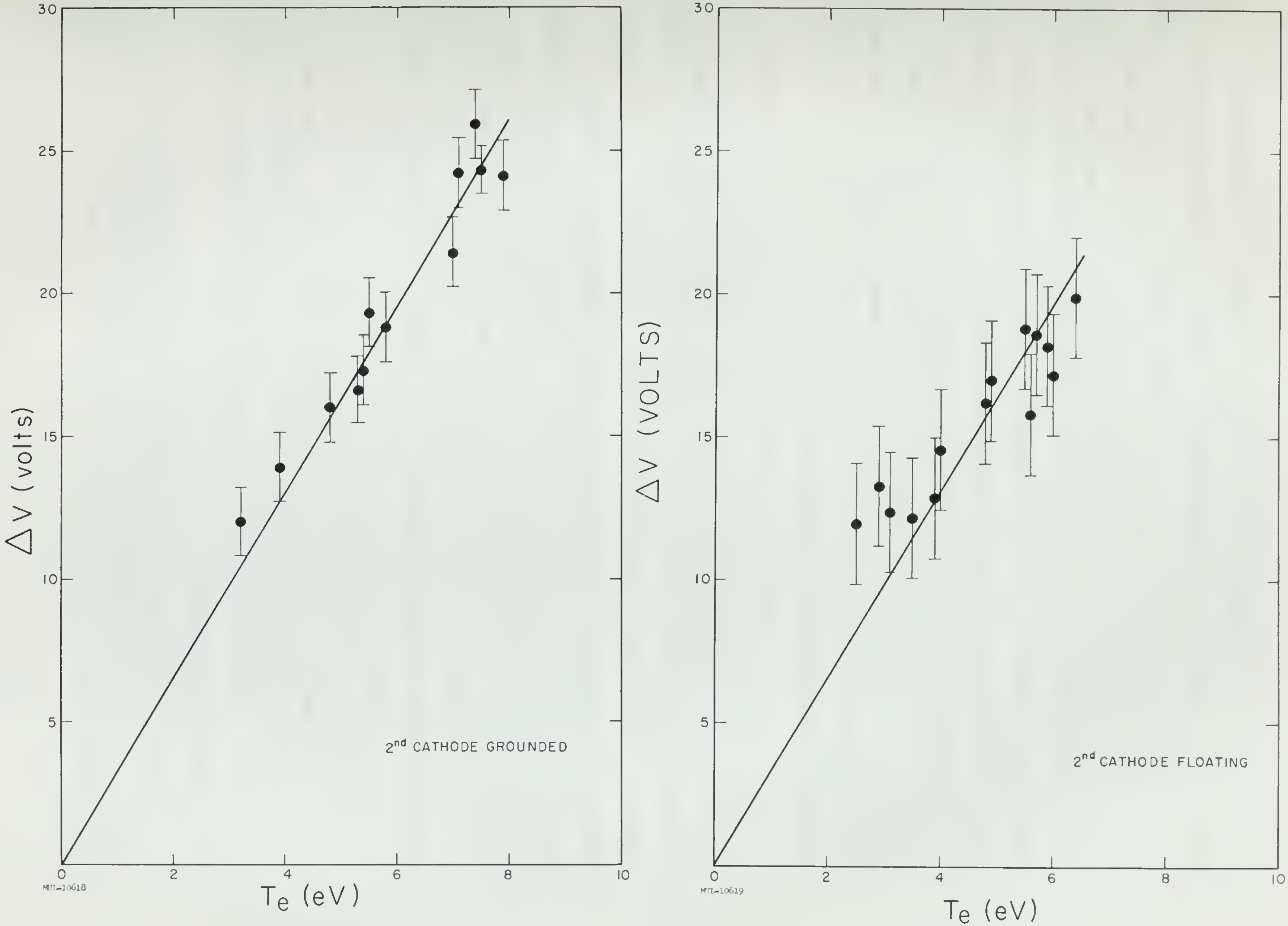

Fig. 7. $\Delta V\ (V_\sigma - V_f)$ vs T_e.

ion density, vs r for both conditions of the cathode. At the values of density which exist in the P-4 plasma as little as 1% disparity between electron and ion density would create electric fields in the kilovolt range. Since fields of this magnitude are not present Fig. 11 also represents the electron density as a function of r. As can be seen, the density at the innermost points is increasing with decreasing radial distance from the beam axis. This is as one would expect, since microwave measurements[9] indicate an average beam density of about 2.3×10^{13} electrons/cm^3.

Figure 12 is a plot of electron temperature as a function of radial distance. It is seen that in the region investigated the temperature is roughly a linear function of the radius. It is expected that when the dense inner core of the plasma is reached, the electron temperature levels off at about the observed ion temperature of 8 ev.

The electron temperature seems to be somewhat lower in the case of single-cathode operation in the region from 1 to 2 cm from the beam axis. This is not unreasonable, since when the cathode is grounded it will reflect the electrons which have diffused radially outward and which approach it from the downstream direction. Furthermore, it will contribute a few energetic electrons to this outer region as a result of secondary emission from the ions which it collects, thus there should be ionization occurring at the edge of the beam due to the refluxing of the fast electrons in this region. In essence it serves to reduce electron losses on the outer portion of the plasma column, thus giving rise to a slightly higher electron temperature than if the only electrons present were due to transverse diffusion out of the beam.

Figures 7a and 7b are plots of $V_\sigma - V_f$ vs T_e. As has been mentioned previously, the plots are used to correct V_σ to V'_σ. The points are plotted with their standard deviations to give some feel for the goodness of fit. In both cases, the fit is considered to be satisfactory under the assumption that when $V_\sigma - V_f = 0$, $T_e = 0$.

Figures 8a and 8b are plots of the V'_σ vs the logarithm of radial distance from the axis. Since the plasma column is cylindrically symmetrical, if no net space charge were present in the range of radii plotted

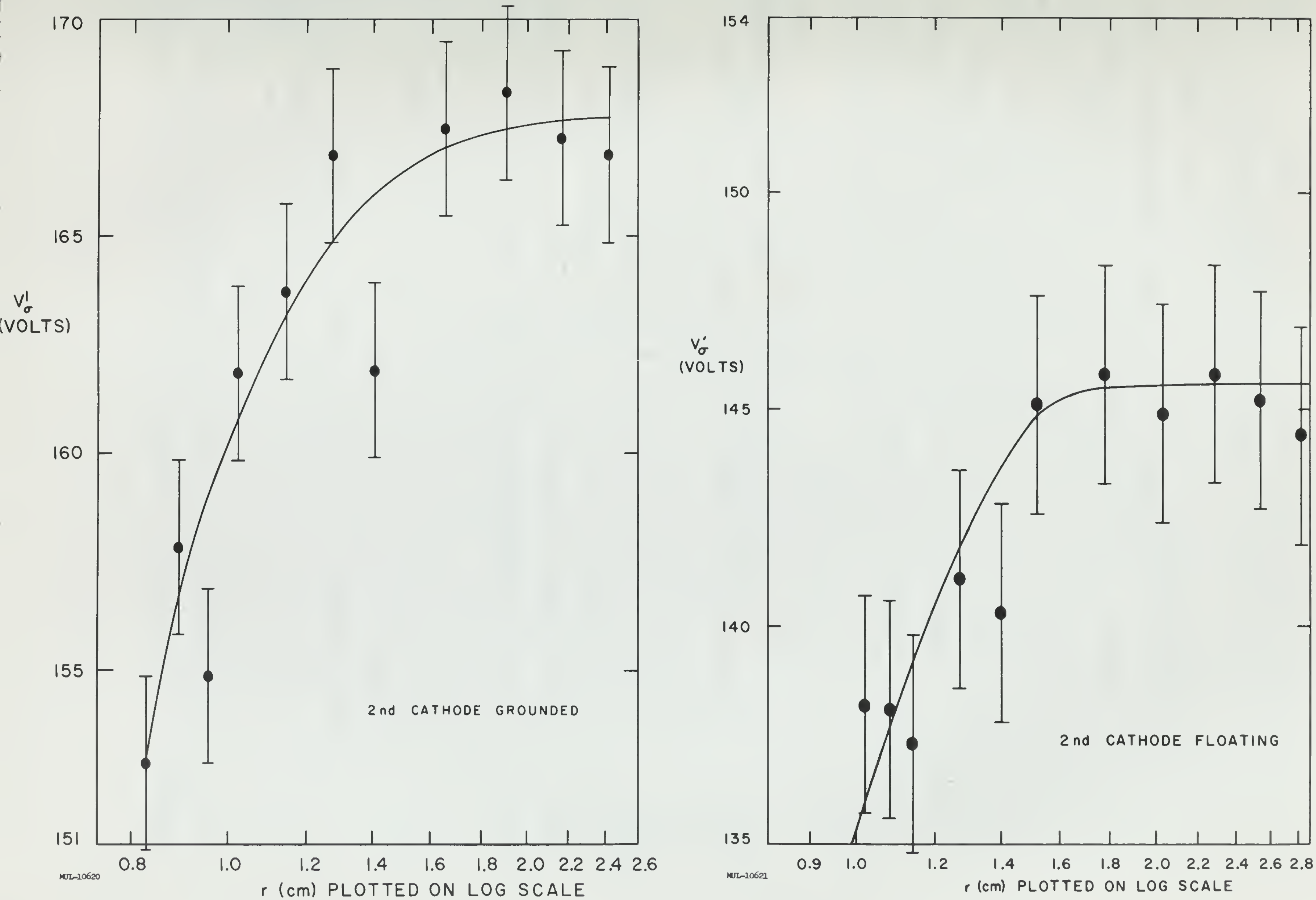

Fig. 8. V'_σ vs Log r.

then (to the extent that V'_σ approximates V_s) this curve would be a straight line with a slope characteristic of the net space charged enclosed inside the smallest radius. A concave curvature toward the log r axis indicates local positive space charge and a convex curvature indicates a local negative space charge. With both double- and single-cathode operating conditions, the variation of $dV/d(\log r)$ with r indicates that the net excess of electrons within a radius r drops from a value of about 1×10^8 excess electrons/cm at about 1 cm to less than a tenth of this value at about 2 cm from the axis, which shows that in this radial interval a net positive space charge of about 10^8 ions per cm of axial length exists. Due to the uncertainty of the slope at these innermost points this can be considered to have only order-of-magnitude accuracy. It is, however, evident that a curvature exists over the region measured in both cases and this curvature indicates a positive space charge.

Figure 9 is merely a translation of the solid curves of Figs. 8a and 8b onto a linear rather than logarithmic radius scale. Since the primary reason for these curves is to show relative shapes in the two different cathode conditions, they have been normalized on the outskirts of the beam. Examination of this figure shows that, to the extent that these curves represent V_s, the space potential decreases more abruptly with decreasing radial distance in the case of single-cathode operation. When the second cathode is allowed to float it is held at essentially anode potential by the plasma on the edge of the beam which encounters it along the magnetic field lines. This means that a more abrupt drop in space potential is expected in single-cathode operation. Conversely when the second cathode is grounded it actually has a tendency to "drag down" the plasma in the outer region of the beam.

By taking derivatives of the curves in Fig. 9, the fields can be estimated. These fields are plotted in Fig. 10. One expects to find the field very small at a large distance from the beam, as is the case. The values of the field obtained in the inner regions are, of course, least accurate due to the uncertainty of the measured values of V_σ at these locations. The fact that the electric field does increase as the distance

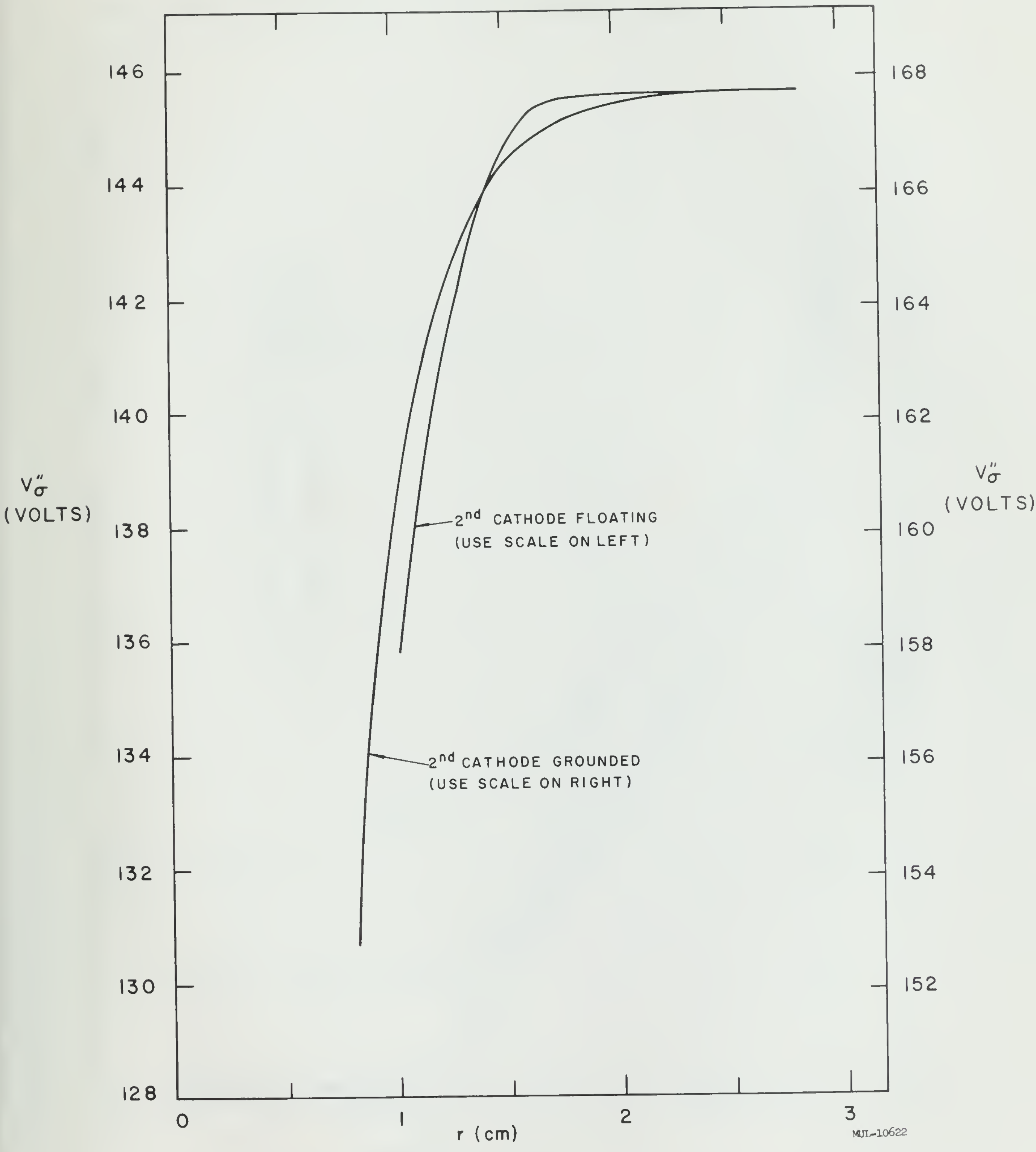

Fig. 9. V''_σ vs r.

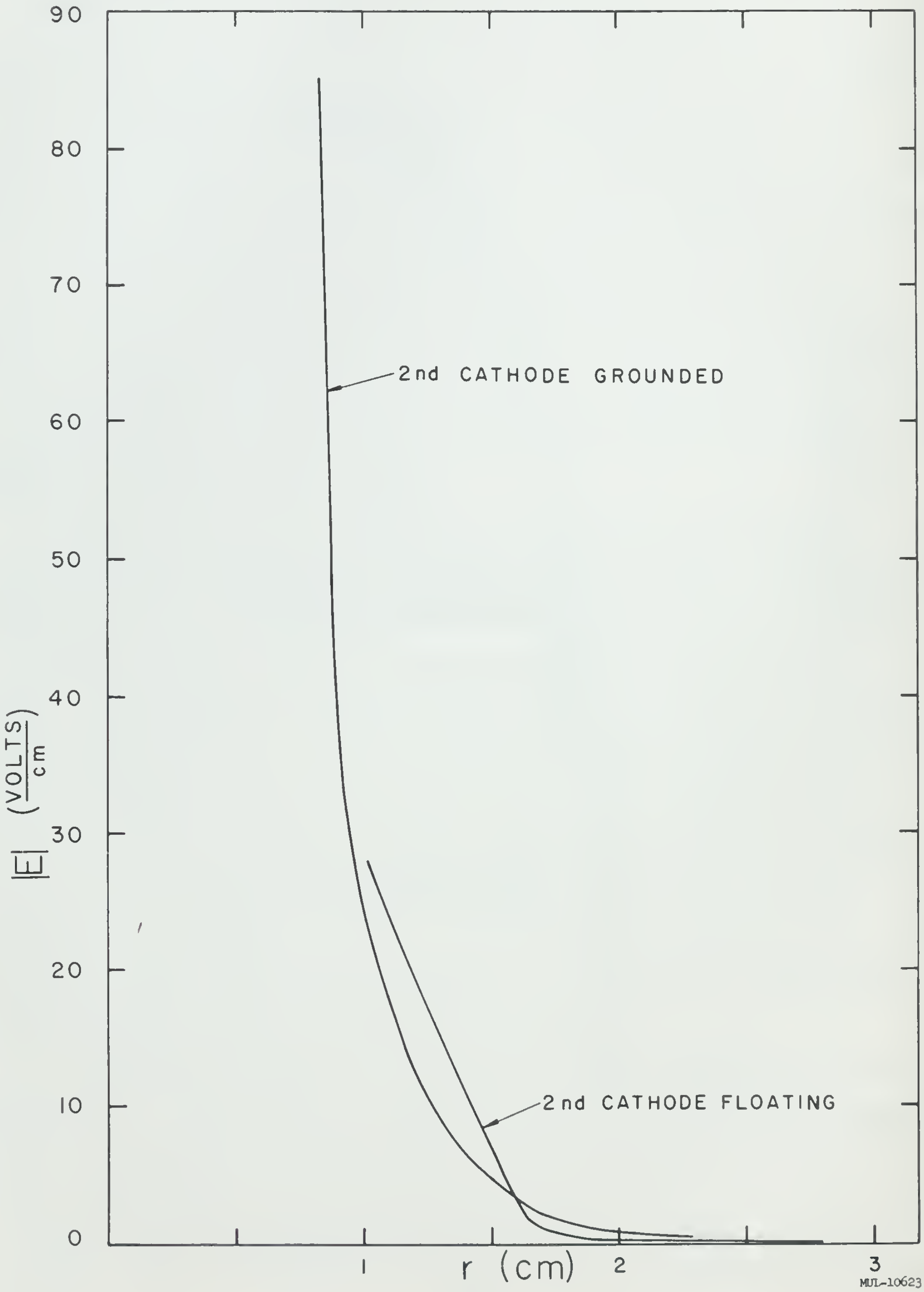
90
80
70
60
50
40
30
20
10
0
$|E|$ (VOLTS/cm)
2nd CATHODE GROUNDED
2nd CATHODE FLOATING
1
2
3
r (cm)
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Fig. 10. $|E|$ vs r.

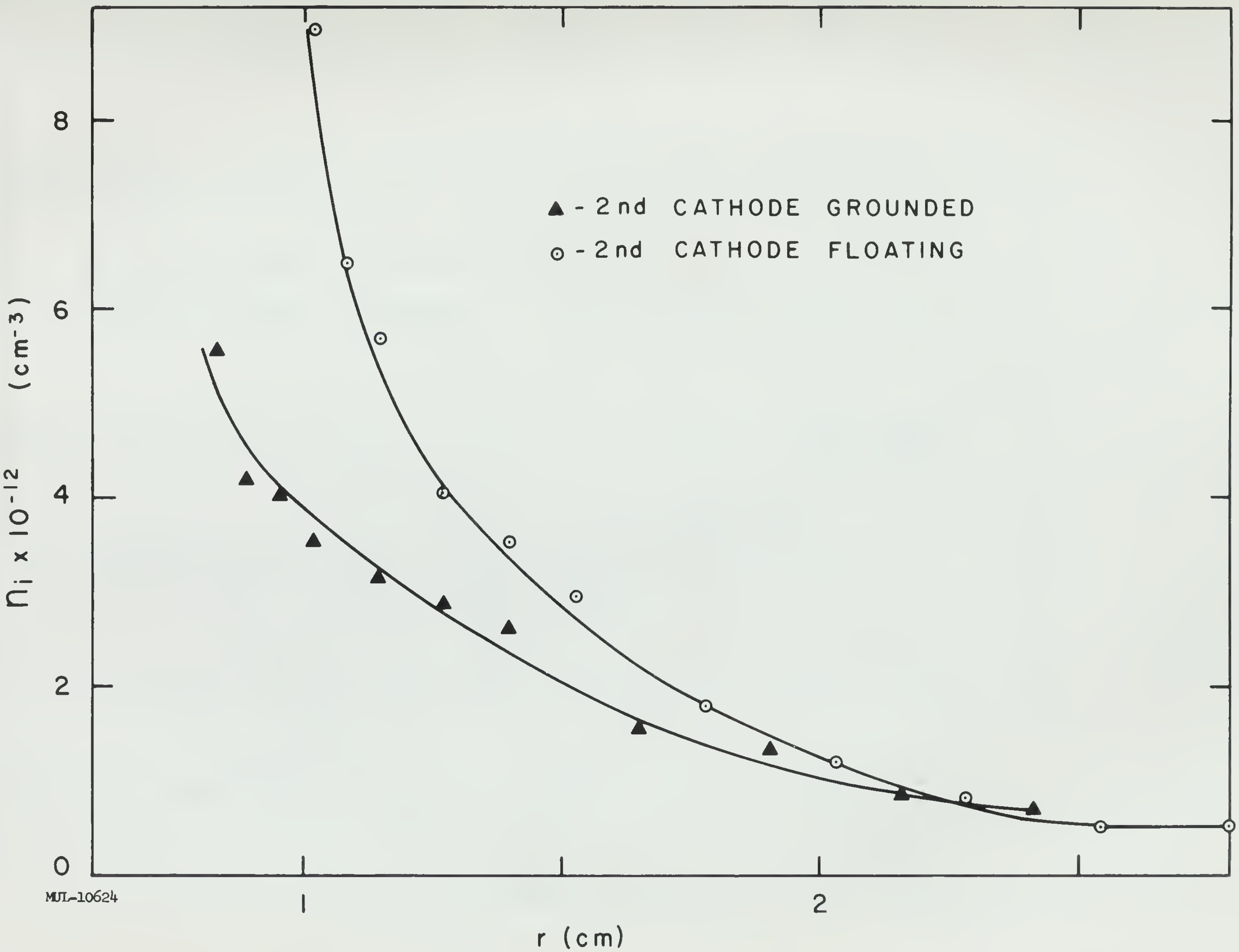
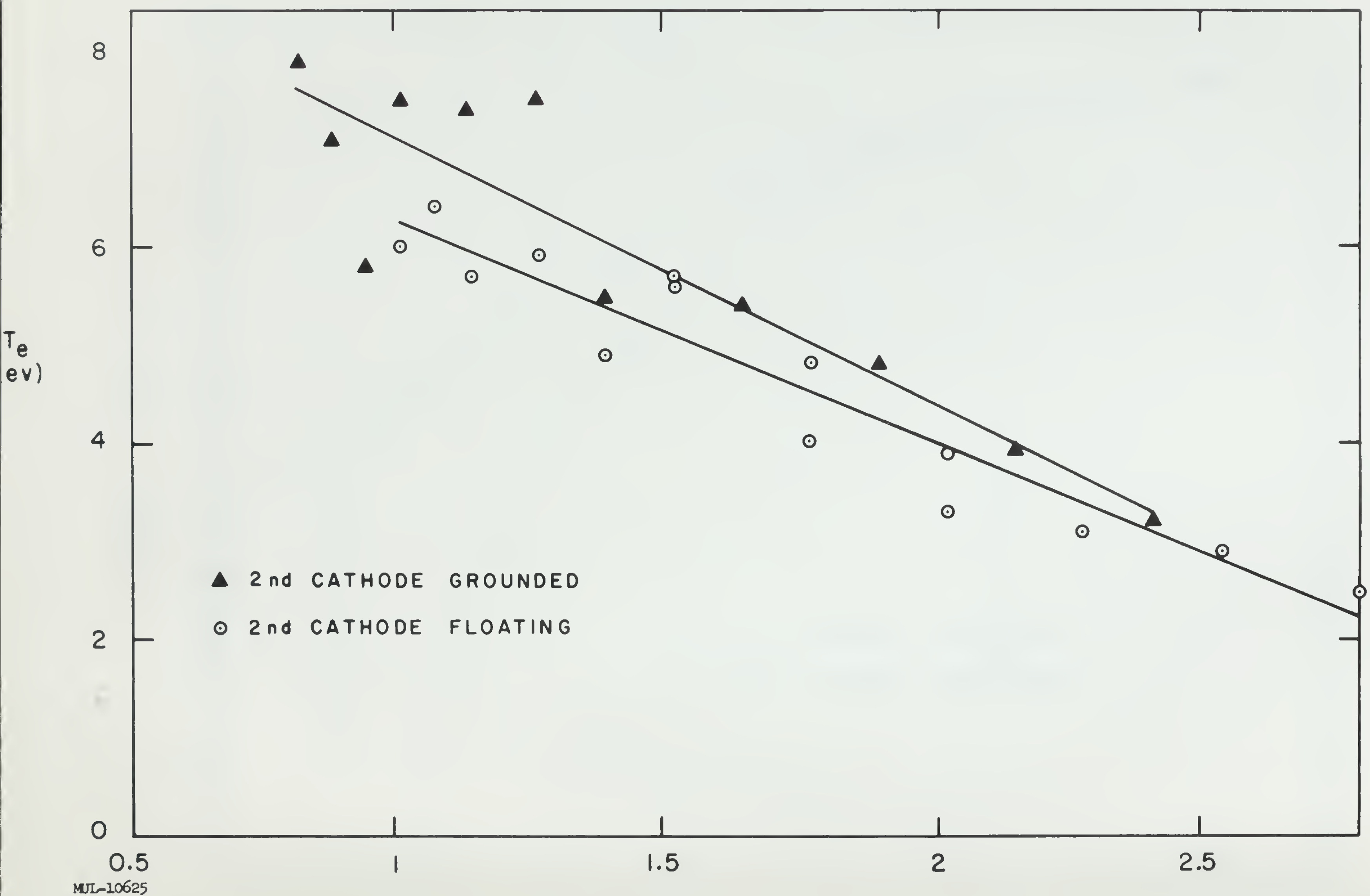

▲ - 2nd CATHODE GROUNDED
⊙ - 2nd CATHODE FLOATING
$n_i \times 10^{-12}$ (cm^{-3})
r (cm)
0
2
4
6
8
1
2
MUL-10624

Fig. 11. n_i vs r.



T_e
ev)
8
6
4
2
0
0.5
1
1.5
2
2.5
r (cm)
2nd CATHODE GROUNDED
2nd CATHODE FLOATING
MUL-10625

Fig. 12. T_e vs r.

from the beam axis decreases is, however, evident. From a symmetry argument it must be realized that the field must go to zero at the axis. Since the fields at the innermost points measured are still increasing with decreasing radial distance, the drop-off must be rather sharp when it occurs.

Table I. Data with Second Cathode Grounded
(V_{anode} = 155 volts)

r (cm)	V_σ (volts)	V_f (volts)	$V_\sigma - V_f$ (volts)	V'_σ (volts)	T_e (ev)	n_i (ions/cm^3)
2.41	168.4	156.4	12.0	166.9	3.2	0.71×10^{12}
2.16	168.4	154.5	13.9	167.3	3.9	0.88 "
1.91	168.6	152.6	16.0	168.3	4.8	1.14 "
1.65	167.1	149.8	17.3	167.5	5.4	1.55 "
1.40	163.2	143.9	19.3	161.9	5.5	2.26 "
1.27	166.6	142.3	24.3	166.9	7.5	2.91 "
1.14	165.4	139.5	25.9	163.7	7.5	3.16 "
1.02	161.4	137.3	24.1	161.9	7.5	3.56 "
0.953	154.7	135.9	18.8	154.9	5.8	4.04 "
0.889	158.8	134.6	24.2	157.8	7.1	4.21 "
0.826	151.1	127.0	24.1	152.9	7.9	5.56 "

Table II. Data with Second Cathode Floating
(V_{anode} = 137 volts)

r (cm)	V_σ (volts)	V_f (volts)	ΔV (volts)	V'_σ (volts)	T_e (ev)	n_i (ions/cm^3)
2.79	148.2	136.2	12.0	144.4	2.5	0.54×10^{12}
2.54	149.0	135.7	13.3	145.2	2.9	0.55 "
2.29	148.0	135.6	12.4	145.8	3.1	0.83 "
2.03	145.6	133.4	12.2	144.9	3.5	1.22 "
1.78	146.3	130.1	16.2	145.8	4.8	1.82 "
1.52	145.0	126.4	18.6	145.1	5.7	2.96 "
1.40	141.2	124.2	17.0	140.3	4.9	3.55 "
1.27	139.9	121.7	18.2	141.1	5.9	4.07 "
1.14	137.4	118.6	18.8	137.3	5.7	5.69 "
1.08	137.0	117.1	19.9	138.1	6.4	6.48 "
1.02	135.7	118.5	17.2	138.2	6.0	8.96 "

SUMMARY

The comparison of the probe measurements made with the second cathode of the P-4 grounded or ungrounded supports the visual evidence of having a more sharply defined plasma beam with the cathode ungrounded. No radical differences between single- and double-cathode operations were observed. However, the fact that in single-cathode operation the beam seems to be more sharply defined may be very important for purposes of other types of experiments which might be conducted on the P-4 machine. One can speculate that the dense inner core of the plasma is essentially unaffected by the potential of the second cathode, but until a complete beam profile can be obtained by other probe techniques or some other method this cannot be verified.

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